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# Livestock manure and crop residue for energy generation: Macro-assessment at a national scale

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ABSTRACT

Livestock manure and crop residue can be processed in an environmentally acceptable way through anaerobic digestion to generate biogas, also, under an integrated production scheme, providing fertiliser and heat as by-products. The most valuable use of the produced biogas (i.e. for the generation of electricity or a gaseous biofuel) depends on specific economic conditions and other constraints which cannot be generalised.

From a GIS-based biomass resource inventory, manure and agriculture residue were evaluated as substrates for the generation of electricity or biomethane for injection into the natural grid, and then comparatively assessed at national level in Chile. Mathematical modelling was used to calculate supply–cost curves for the purpose of estimating the representative generation cost of both secondary energy end-products as well as their technical and economic potential. The mono-digestion of manure and mono-digestion of agricultural residue as well as the co-digestion of both substrates were assessed.

From manure processing, the estimated economic potential was 0.8 $TWh_e\ y^{-1}$ of electricity at a representative generation cost of 25 ct€ $kWh_e^{-1}$, while that of biomethane was calculated to be 182 MM $Nm^3\ y^{-1}$ at a representative generation cost of 98 € MM $BTU^{-1}$. In addition, the economic potential for the mono-digestion of agricultural residue was estimated to be 1.1 $TWh_e y^{-1}$ at a representative generation cost of 15.4 ct€ $kWh_e^{-1}$, while that of biomethane generation was 280 MM $Nm^3\ y^{-1}$ at a generation cost of 40 € MM $BTU^{-1}$. Manure co-digestion offered a significant increase of roughly 46% of the economic potential at the same representative cost as mono-digestion. The co-digestion option of using biomethane production for injection does not seem to be adequate when considering a national policy to boost biogas production. Electricity generation, however, may be a viable option that has major economic advantages with or without a feed-in tariff scheme.

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## 1. Introduction

The production of biogas through anaerobic digestion, a state-of-the art technology, has recently attracted considerable attention as a means of generating energy, given its significant environmental, social and political benefits – a fact supported by a series of studies in the field [1–5]. However, unlike other alternative technologies for sustainable energy generation, it is associated with a number of uncertainties, making generalisation of technical or economic potential at a national or regional level difficult. This is principally due to the diversity of potentially suitable raw material substrates, the geographical distribution of the resource, scale of generation, not to mention local environmental and energy policies, which demand a case-by-case analysis [6].

Anaerobic digestion is particularly attractive when searching for an environmentally friendly solution for the sustainable disposal of manure generated by farms [7]. While the intensification of farming practices has brought about an increase in the production of edible goods, this increase has inevitably led to growth in the volume of manure, thus creating higher disposal cost and posing a risk to the environment. Although manure has historically been employed as a natural fertiliser to increase the quality of farmland and return nutrients to the soil, its employment can be responsible for the eutrophication of waterways, and the loss of nitrate or phosphate when applied at non-optimal rates [8].

In recent years, Chile's livestock industry has undergone considerable development. The country was a net importer of dairy products until 2001, at which point a surplus in production made it a net exporter. The poultry industry supplies most of the internal demand with 594,000 t $y^{-1}$ (data from 2010) accounting for 45% of the total demand of meat. Pork follows with 498,000 t $y^{-1}$ (expressed as dressed meat), and has exhibited steady growth throughout the last decade (6.7% annually). Both are attributable to higher demand from export markets such as South Korea and Japan as well as an internal increase in consumption [9]. The dairy industry is made up of approximately one hundred medium and large milk supplying plants principally located in the central and southern zones [9]. In the context of the expansion of the feedstock industry, the country needs to confront this new environmental challenge in order to ensure its long-term economic competitiveness in a sustainable fashion. The introduction of anaerobic technologies is seen as a promising approach to overcoming this environmental issue.

The production of biogas from manure can be supported by adding co-substrates to increase the biogas yield [10] and the content of methane in the gas, thus improving reactor efficiency and, in turn, the economic viability of the plant. This is a plausible possibility as feedstock industries are normally located near agricultural complexes where residues are, to some extent, readily available. However, the supply of biomass is limited by logistical issues and the cost of substrates. The agricultural residue available after harvesting straw, stover, leaves or cobs can be used as a co-substrate for biogas generation. Nevertheless, this residue must be employed in a sustainable way, with respect to ensuring that the rate of removal does not have a detrimental effect on soil fertility [11].

Much attention has been given to assessment of biogas generation from manure and crop residue in large areas [12,13], mainly as a consequence of the environmental gains already mentioned, but also because of the rural development opportunities and the contribution it could make towards renewable energy generation goals [14]. With this in mind, Sliz-Szkliniarz and Vogt [15] sought to assess potential sites for the anaerobic co-digestion of manure and crop silage in the region of Kijawsko-Pomorske, Poland. Through a GIS approach, spatial data was integrated to calculate the cost of electricity production and biomethane for injection into the grid. They concluded that the introduction of incentives is needed to boost the use of biogas and, therefore, to reach the goal set by the government. Tranter et al. [16] assessed the potential for energy production from on-farm digestion in England, and analysed the main barriers to the implementation of anaerobic digestion. In that study, the figures are expressed as a technical potential, and no information on the spatial distribution of farms or cost of production is given. Lantz [17] assessed the production of energy by combined heat and power (CHP) using manure in Sweden, and came to the conclusion that energy production is not profitable under the current conditions and that policy instruments are needed to make it economically viable. Moreover, it was concluded that a major impact on the economics of the process lay in the use of electricity and heat, whereas digestate utilisation as by-product played only a marginal role. Finally, Yabe's [18] study considered Hokkaido, an 83,000 $km^2$ island in Japan. This study aimed to select a location for biogas plants in each county and evaluate the cost of production for electricity from cow manure by using a GIS-based method to estimate the required number and location of centralised biogas plants. Most recently, a study by Höhn et al. [19] attempted to determine energy potential and feasible location of biogas plants in southern Finland by using a GIS-based method. The methodology focused on minimising the transportation distance for feedstock so that an optimal allocation could be found. In this study, no economic assessment was conducted.

In Chile the introduction of on-farm anaerobic technology has been slow and has taken place only recently. Total biogas generation reached a mere 0.4 PJ $y^{-1}$ in 2011 [20] but, nonetheless, preliminary evaluations have shown that the theoretical potential of biogas is roughly 15 PJ $y^{-1}$ and 9 PJ $y^{-1}$ from the digestion of manure and crop residue [21], suggesting that less than 2% of the potential is currently being realised.

The use of residue seems to be the most reasonable starting point for the development of an energy production strategy focused on biogas because it brings direct environmental advantages. The use of energy crops does not seem to be appropriate for implementation, at least at the first stage as it would be unwise for Chile to change the land currently used for food production and force the country to revert to imports in order to address internal consumption for biofuel production [22]. Although the biofuel alternative has not been thoroughly assessed at a national level yet, either technically or economically, preliminary evaluations indicate that the main constraints arise from the limited suitable land available for the most promising crops both for liquid and gaseous biofuels [23].

The present research seeks to assess the potential of biogas production based on the utilisation of manure and crop residues as mono-substrates, and to assess the possibility of co-digesting them. The assessment includes a cross-economic comparison between the possibility of using biogas for electricity or for gaseous fuel production. The geographical parameter used to conduct the evaluation is

**Acronyms, Nomenclature and Units**

| | |
|---|---|
| Bio-SNG | substitute natural gas from biomass |
| BTE | biogas-to-energy |
| BTU | biogas-to-upgrade |
| CHP | combined heat and power |
| GIS | geographical information system |
| $i$ | cost of capital (%) |
| MM | abbreviation of one million ($10^6$) |
| $\pi_t$ | technical limit (technical potential) |
| $\pi_e$ | economic limit (economic potential) |
| y | abbreviation for year |
| $x_{t,i}$ | index $i$ of a variable $x_t$ |
| ct€ | euro cents |
| $GWh_e$ | gigawatt-hour electric |
| $GWh_{th}$ | gigawatt-hour thermal |
| ha | hectare, equal to 10,000 $m^2$ |
| MMBTU | one million British thermal units, 1 MMBTU= 293.29 $kWh_{th}$ |
| $Nm^3$ | normal cubic metre |
| mqq | metric quintal, equal to 100 kg |
| t | metric tonne (1000 kg) |

the entire country of Chile, and the current conditions are taken as the framework for the economic assessment. The forthcoming sections cover an analysis of the livestock and agricultural sectors, outline the assumptions on which the assessment is based, and explain the methodological approach used for the analysis of potential and the macro-economic assessment.

This work is in line with previous studies towards the construction of the biomethane roadmap of Chile [24,25], a characterisation which will help develop a national strategy for bioenergy.

## 2. Livestock and agricultural characterisation

The total area of Chile is 2,006,096 $km^2$, and it is divided into 14 administrative regions of differing area (see Table 1). The climatological diversity of the country enables the production of a variety of agricultural and livestock products. The total livestock is composed of an estimated 11.7 million heads [26] consisting of 32% bovine, 33% ovine and 25% swine. Table 2 lists the data organised by administrative region. As can be observed, the livestock is mainly concentrated in Región de Magallanes (XII) (20%), Región de los Lagos (X) (13%) and Región Metropolitana (XIII) (12%).

Regarding annual crops, the predominant species in terms of percentage of the total cultivated area are wheat (40%), corn (19%), oats (15%) and potatoes (10%). At the regional level, 69% of wheat and 85% of oat crops are concentrated in Región del Bio-Bio (VIII) and Región de la Araucanía (IX), whereas corn is cultivated mainly in Región de O´Higgins (IX) and Región del Maule (VI), comprising 75% of the total area. Finally, potato plantations are distributed throughout the country although more significantly concentrated in the south.

Annual crop plantations have declined during recent decades. For the 2010–2011 period, a decrease of roughly 18% can be observed in the total cultivated area compared to the previous period of equal length. This decrease has not been uniform, with more substantial decreases occurring in wheat, vegetables, sugar beets, rape and potatoes. This fall has been partly counterbalanced by the cultivation of corn, oats, barley and lupine. On the contrary, a rise in the average productivity is noted in virtually all crops, reaching high values when compared internationally [9] (see Table 3).

**Table 1**
Regions of Chile, number of counties and surface [67].

| Region's name | Region's Roman numeral | Number of counties per region | Region's surface ($km^2$) |
|---|---|---|---|
| Región de Tarapacá | I | 7 | 42,225.8 |
| Región de Antofagasta | II | 9 | 126,049.1 |
| Región de Atacama | III | 9 | 75,176.2 |
| Región de Coquimbo | IV | 15 | 40,579.9 |
| Región de Valparaíso | V | 38 | 16,396.1 |
| Región de O'Higgins | VI | 33 | 16,387.0 |
| Región del Maule | VII | 30 | 30,296.1 |
| Región del Biobio | VIII | 54 | 37,068.7 |
| Región de la Araucanía | IX | 32 | 31,842.3 |
| Región de los Lagos | X | 30 | 48,583.6 |
| Región de Aysén | XI | 10 | 108,494.4 |
| Región de Magayanes y Antártica | XII | 11 | 1,382,291.1 |
| Región Metropolitana | XIII | 52 | 15,403.2 |
| Región de los Ríos | XIV | 12 | 18,429.6 |
| Región de Arica y Parinacota | XV | 4 | 16,873.3 |
| **Total**[a] | | **346** | 2,006,096 |

[a] Total area including Antártica.

## 3. Technologies for biogas utilisation

Although simplified, Fig. 1 illustrates in diagrammatic form the process of biochemical conversion of biomass for the generation of energy. It starts with the procurement of biomass to be fed into an anaerobic reactor. While this is a generalised example with the provision of biomass obtained from agricultural residue, energy crops or others, the biomass can be generated locally and processed in situ, as is normal for manure in farming facilities, and hence does not involve any additional logistical cost.

During the digestion of biomass, in which bacteria ferment organic matter in an oxygen-free environment, biogas is generated. This gas is constituted mainly of methane (40–70%), carbon dioxide (30–60%) [27] and a complex mixture of trace compounds [28]. Normally, biogas must be desulphurised to acceptable levels (50–60 ppm) for any practical application since the presence of sulphurised-compounds can cause damage to the piping, fittings and machinery [29].

The most straightforward way of using biogas is through combustion for electricity generation. Reciprocating engines for electricity are by far the dominant technology for electricity generation [30]. It is a reliable technology and electricity can be generated in varying power profiles (1 $kW_e$ to 6 $MW_e$) although thermal and electrical efficiency is highly dependent on capacity. The combustion principle can be based either on spark-ignition, with engines that work with the Otto cycle, or through compression ignition, which operates under a diesel-cycle akin to a vehicle engine [30]. Because a mixture of biogas and air cannot fulfil the conditions necessary for ignition when compressed, the spark-ignition engines demand a supplementary fuel such as diesel, biodiesel or vegetable oil [31]. Modern spark-ignition engines typically operate with 10% supplementary ignition fuel. However, consumption in the 3–30% range has also been reported [17].

In contrast to the reciprocating engines, Stirling engines have an operating principle based on the continuous expansion and compression of a confined gas, which allows the pistons to move up and

**Table 2**
Livestock (per 1,000 heads) by category and region in Chile (data from 2007) [26].

| Country region's name | Bovine | Sheep | Swine | Equine | | | Goat | Camelid | | Wildboar | Deer | Rabbit | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Horse* | *Mule* | *Donkey* | | *Alpaca* | *Llama* | | | | |
| Región de Tarapacá (I) | 0.1 | 10.0 | 1.4 | 0.0 | 0.1 | 0.6 | 2.3 | 3.5 | 23.7 | 0.0 | 0.0 | 6.7 | **48.5** |
| Región de Antofagasta (II) | 0.3 | 10.5 | 1.9 | 0.5 | 0.0 | 0.8 | 6.2 | 0.2 | 5.6 | 0.0 | 0.0 | 8.6 | **34.6** |
| Región de Atacama (III) | 7.1 | 5.2 | 1.4 | 3.9 | 0.7 | 3.4 | 39.2 | 0.0 | 0.0 | 0.0 | 0.0 | 2.5 | **63.6** |
| Región de Coquimbo (IV) | 41.3 | 84.2 | 3.8 | 25.7 | 3.9 | 8.8 | 404.6 | 0.1 | 0.2 | 0.0 | 0.0 | 2.9 | **575.4** |
| Región de Valparaíso (V) | 102.7 | 30.3 | 173.8 | 26.7 | 0.7 | 1.0 | 45.5 | 0.2 | 0.2 | 0.0 | 0.0 | 2.9 | **384.0** |
| Región de O'Higgins (VI) | 83.4 | 157.6 | 860.0 | 26.8 | 0.2 | 0.0 | 18.5 | 0.5 | 0.1 | 0.0 | 0.0 | 5.1 | **1,152.3** |
| Región del Maule (VII) | 258.2 | 155.1 | 93.4 | 54.0 | 0.5 | 0.1 | 40.1 | 0.4 | 0.0 | 0.2 | 0.5 | 1.5 | **604.1** |
| Región del Bío-Bío (VIII) | 449.4 | 173.7 | 179.8 | 51.3 | 0.1 | 0.0 | 47.3 | 0.1 | 0.2 | 0.9 | 0.2 | 3.1 | **905.9** |
| Región de la Araucanía (IX) | 668.1 | 277.9 | 199.6 | 30.9 | 0.1 | 0.0 | 50.8 | 0.5 | 0.7 | 1.0 | 0.7 | 2.2 | **1,232.6** |
| Región de los Lagos (X) | 1,047.2 | 315.2 | 79.8 | 22.8 | 0.0 | 0.0 | 11.1 | 0.5 | 0.3 | 0.9 | 4.4 | 0.9 | **1,483.1** |
| Región de Aysen (XI) | 193.8 | 304.9 | 2.7 | 12.2 | 0.1 | 0.0 | 12.1 | 0.2 | 0.0 | 0.0 | 0.0 | 0.1 | **526.2** |
| Región de Magallanes (XII) | 141.8 | 2,205.3 | 1.7 | 10.2 | 0.0 | 0.0 | 0.1 | 0.4 | 0.1 | 0.0 | 0.0 | 0.1 | **2,359.6** |
| Región Metropolitana (XIII) | 101.3 | 24.0 | 1,292.7 | 24.5 | 0.2 | 0.1 | 12.3 | 0.0 | 0.1 | 0.2 | 0.0 | 5.7 | **1,461.1** |
| Región de los Ríos (XIV) | 621.6 | 116.1 | 34.3 | 14.3 | 0.0 | 0.0 | 9.3 | 0.5 | 0.4 | 0.7 | 0.1 | 0.3 | **797.7** |
| Región de Arica y Parinacota (XV) | 2.3 | 18.2 | 2.3 | 0.3 | 0.1 | 0.1 | 6.0 | 19.1 | 17.4 | 0.0 | 0.0 | 1.0 | **66.9** |
| ***Total country*** | ***3,719*** | ***3,888*** | ***2,929*** | ***304*** | ***7*** | ***15*** | ***706*** | ***26*** | ***49*** | ***4*** | ***6*** | ***44*** | ***11,696*** |

**Table 3**
Productivity of crops and total exploited surface at national level [26].

| Species ($l=\overline{1,n}$) | Average productivity $p_l$ (mqq ha$^{-1}$ y$^{-1}$) | Total surface (ha) |
|---|---|---|
| 1. Beer barley | 50.62 | 11,108 |
| 2. Barley | 41.52 | 5,983 |
| 3. Beans (for export) | 20.81 | 1,153 |
| 4. Beans (for internal consumption) | 17.02 | 9,633 |
| 5. Bread wheat | 52.36 | 9,198 |
| 6. Chickpeas | 8.94 | 2,940 |
| 7. Corn | 108.32 | 102,955 |
| 8. Grass pea | 8.34 | 255 |
| 9. Lentils | 8.43 | 861 |
| 10. Oats | 41.80 | 81,480 |
| 11. Others | n.a. | 1,061 |
| 12. Others cereals | n.a. | 6,187 |
| 13. Peas | 14.10 | 1,258 |
| 14. Potatoes | 154.54 | 53,731 |
| 15. Quinoa | 6.08 | 1,427 |
| 16. Rice (with peel) | 50.77 | 21,579 |
| 17. Rye | 44.97 | 1,115 |
| 18. Tapicoa | 1.35 | 5.18 |
| 19. Tricale | 48.18 | 19,243 |
| 20. White wheat | 47.77 | 219,126 |
| **Total country** | – | **550,303** |

down, generating mechanical energy for subsequent electricity production by a generator [32]. Microturbines can generate electricity and heat in a low range (0.5–200 $kW_e$) and can be powered by natural gas, propane, hydrogen, diesel as well as biogas. The electrical efficiency of microturbines can reach roughly 30% [33].

A second option is to use biogas leaving the anaerobic digester as raw material for the production of a gaseous biofuel. This route involves upgrading, and basically implies that carbon dioxide uptake is required to increase the fuel heating value [34]. In addition to this, hydrogen sulphide and other trace compounds as well water are removed. The main product from this processing is called biomethane and has numerous applications, for instance, as fuel for transportation, whether compressed, liquefied under cryogenic conditions [35] or stored in fuel cells [36]. When considering the injection of biomethane into the natural gas grid, previous operations of odorisation and adjustments of the Wobbe Index are needed so that the end-product can reach the same standard as the natural gas with which it will be mixed. For this reason, it is normally referred to as "bio-substitute of natural gas", or by its acronym Bio-SNG [37].

The conversion of biomass can then be performed either through a *biogas-to-energy* route, from which electricity and heat are the main products, or via a *biogas-to-upgrade* conversion route, from which a gaseous fuel called Bio-SNG can be generated. Independently of the conversion pathway, a digestate from the anaerobic digestion is produced as a by-product with the potential application as a fertiliser for agriculture [38].

## 4. Methodology

In this section, the methodology applicable for the analysis of potential is presented and the processing of manure and agricultural crop residue via mono-digestion as well as the co-digestion of both substrates are considered. The evaluation is conducted for the two conversion routes previously described, *biogas-to-energy* and *biogas-to-upgrade*. The scope of this study is the total geographical area of the country and, furthermore, the study takes into account the current economic conditions that are principally reflected in the specific cost, investments and market prices of energy.

### 4.1. Methodology for the potential analysis

#### 4.1.1. Technical potential of biogas from manure mono-digestion

The primary information on the existing farms in Chile used for the assessment was provided by the Department of Studies and Agrarian Policies (ODEPA) from the Ministry of Agriculture. This data includes the total existing heads of livestock within the country (data from 2007) and is broken down by type of livestock (bovine, ovine, swine, etc.) for each farm at county level. The database comprises approximately 87,000 farms distributed throughout the country. With this data, the technical potential ($\pi_t$) of the *biogas-to-energy* (BTE) and *biogas-to-upgrade* (BTU) pathways can be calculated for each $j$th-farm by applying Eqs. (1) and (2) (see Fig. 2).

$$\pi_{t,j}^{BTE}=\sum_k N_{j,k}M_kS_kR_k\Delta\tilde{H}_{LHV}^{CH_4}\eta_a\eta_eA_e \quad \begin{cases} A_e=1;\ \forall\pi_{t,j}^{BTE}>\ 8\mathrm{kW_e} \\ A_e=0;\ \forall\pi_{t,j}^{BTE}\le 8\ \mathrm{kW}_e \end{cases} \tag{1}$$

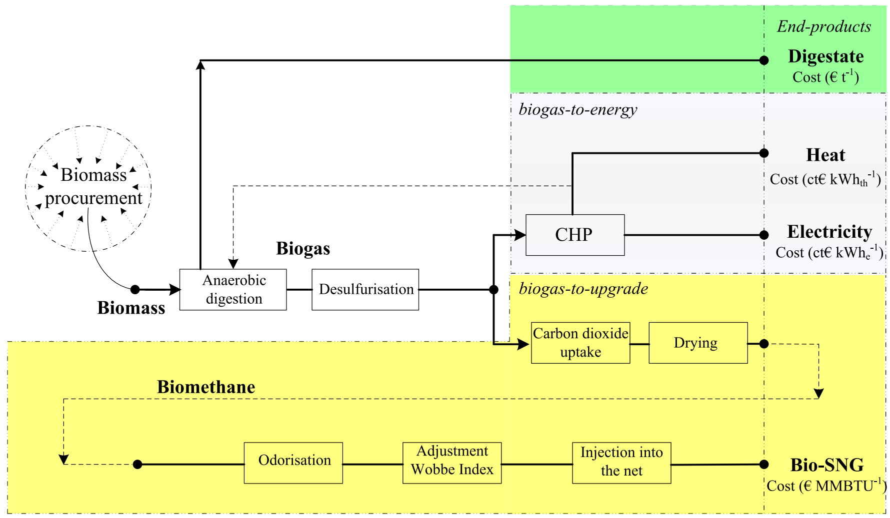


**Fig. 1.** Schematic biogas flow diagram and the two options to be assessed, i.e. electricity and Bio-SNG for the processing of general substrates.

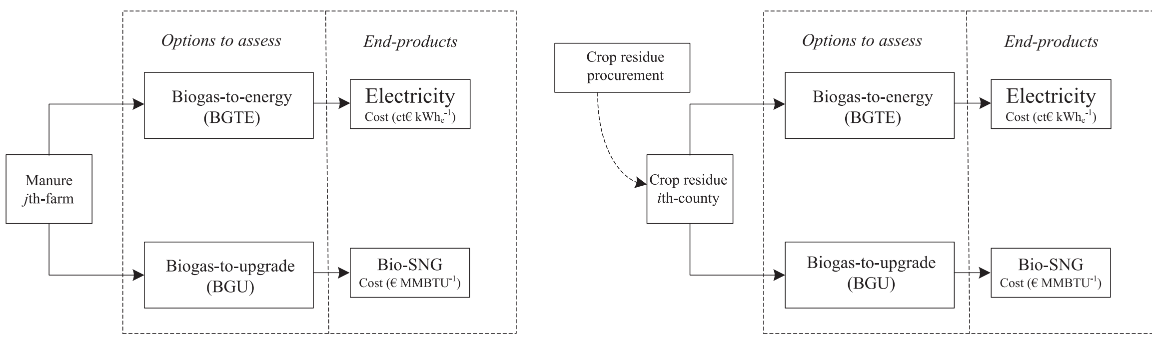


**Fig. 2.** Conversion pathways to assess for the utilisation of manure and crop residue for the production of either electricity or Bio-SNG through mono-digestion.

$$\pi_{t,j}^{BGU} = \sum_k N_{j,k} M_k S_k R_k \eta_a A_u \quad \begin{cases} A_u = 1; \forall \pi_{t,j}^{BGU} > 5\ \mathrm{Nm^3_{CH_4}\ h^{-1}} \\ A_u = 0; \forall \pi_{t,j}^{BGU} \le 5\ \mathrm{Nm^3_{CH_4}\ h^{-1}} \end{cases} \tag{2}$$

In which ($N_{j,k}$) represents the number of livestock heads in the $j$th-farm of the $k$th-species; $\Delta\tilde{H}_{LHV}^{CH_4}$ is the lower heating value of methane and estimated as 50,000 kJ kg$^{-1}$ [39]; and ($\eta_e$) is the electrical efficiency. For the $k$th-species: $M_k$ is the amount of manure produced per head of livestock yearly; $S_k$ is the volatile-to-total wet manure ratio; $R_k$ is the yield of biomethane per volatile solid; $LSU_k$ is the livestock unit; and the manure availability factor is ($\eta_a$). By using the values shown in Table 4, the biogas yield reaches 0.37 Nm$^3$ LSU$^{-1}$ d$^{-1}$ for dairy and 0.59 LSU$^{-1}$ d$^{-1}$ for swine. These values are conservative when compared with data reported in the literature [10].

A Boolean restriction was included to set up the minimal output-capacity for the conversion units, defined as $A_e$ and $A_u$ for the *biogas-to-energy* and *biogas-to-upgrade* routes as indicated in Eq. 1 and Eq. 2. Thus 8 kW$_e$ was considered as the minimum output- capacity for reciprocating engines, while 5 Nm$^3_{CH_4}$h$^{-1}$ was the value for upgrading units. These values correspond to the smallest nominal capacities of commercial units according to technical information [40,41]. Table 4 lists the employed parameters gathered from literature and used for the estimation of the technical potential [10] [42–45].

#### 4.1.2. *Technical potential of biogas from mono-digestion of crop residue*

The annual amount of residue from seasonal crops was calculated using residue-to-crop production ratios, productivity per crop and planted area in a county. Because of the lack of more specific information, some parameters were assumed applying conservative criteria. The technical potential of *biogas-to-energy* and *biogas-to-upgrade* routes (see Fig. 2) can be calculated through Eqs. (3) and (4) as follows:

$$\pi_{t,i}^{BTE} = \sum_l M_l S_l f_l (1-H_l) \Theta_l p_l a_{i,l} \Delta\tilde{H}_{LHV}^{CH_4} A_e \eta_e \quad \begin{cases} A_e = 1; \forall \pi_{t,i}^{BTE} > 8\ \mathrm{kW_e} \\ A_e = 0; \forall \pi_{t,i}^{BTE} \le 8\ \mathrm{kW_e} \end{cases} \tag{3}$$

$$\pi_{t,i}^{BTU} = \sum_l M_l S_l f_l (1-H_l) \Theta_l p_l a_{i,l} A_u \quad \begin{cases} A_u = 1; \forall \pi_{t,i}^{BGU} > 5\ \mathrm{Nm^3_{CH_4}\ h^{-1}} \\ A_u = 0; \forall \pi_{t,i}^{BGU} \le 5\ \mathrm{Nm^3_{CH_4}\ h^{-1}} \end{cases} \tag{4}$$

In which $\pi_{t,i}$ is the technical potential from the $i$th-county, either electricity or Bio-SNG. For the $l$th-crop species within the $i$th-county, $M_l$ corresponds to the methane yield; $S_l$ is the volatile-to-total solid ratio; $f_l$ is the residue-to-crop production ratio; $H_l$ is the humidity assumed at 15% (wet basis); $p_l$ is the crop average productivity (see Table 3); $\Theta_l$ is the sustainable rate removal; and $a_{i,l}$ is the occupied area of the $i$th-county by $l$th-crop. The remaining parameters correspond as defined in Eqs. (1) and (2). In this calculation, it is implicitly assumed that the conversions from biomass into biogas within each county are done at single centralised biogas plants. This assumption is put forward since there is no further information on the geographical distribution of crop residue after harvesting to conduct a more detailed assessment. This point and its implications will be discussed more broadly in the section on economic modelling for cost estimation.

**Table 4**
Parameters employed for the calculation of biogas potential of liquid manure. $M$: average animal weight, $S$: volatile solid and total solid ratio, $R$: biogas yield, $\eta_a$: manure availability factor.

| Livestock ($k=\overline{1,n}$) [j] | Manure per head, $M$ ($kg_m$ $head^{-1}$ $y^{-1}$) [a] | volatile-to-total wet manure ratio, $S$ ($kg_{vs}$ $kg_m^{-1}$) [a] | Specific methane yield, $R$ ($Nm^3$ $kg_{vs}^{-1}$) | Livestock unit (LSU) [h] | Availability factor [i] $\eta_a$ |
|---|---|---|---|---|---|
| 1. Dairy | 20,090 | 0.12 | 0.230 [b] | 1.2 | 0.45 |
| 2. Beef | 7,261 | 0.12 | 0.230 [b] | 0.6 | 0.45 |
| 3. Veal | 2,059 | 0.04 | 0.230 [b] | 0.6 | 0.45 |
| 4. Other (Ox, butt, etc.) | 15,695 | 0.12 | 0.230 [b] | 0.7 | 0.45 |
| 5. Sheep–Ovine | 394 | 0.23 | 0.248 [b] | 0.05 | 0.35 |
| 6. Swine | 6,132 | 0.10 | 0.265 [b] | 0.5 | 0.8 |
| 7. Equine (Horse, mule and donkey) | 8,377 | 0.20 | 0.165 [b] | 1.1 | 0.1 |
| 8. Goat | 958 | 0.22 | 0.248 [b] | 0.05 | 0.1 |
| 9. Camelid (Alpaca and llama) | 958 | 0.22 | 0.165 [c] | 1 [g] | 0.1 |
| 10. Wild boar | 6,132 | 0.10 | 0.265 [d] | 0.5 [g] | 0.1 |
| 11. Deer | 958 | 0.22 | 0.165 [e] | 0.1 [g] | 0.1 |
| 12. Rabbit | 58 | 0.18 | 0.174 [f] | 0.01 [g] | 0.1 |

[a]ASAE [42], [b]Pascual [43], [c]Estimated as equine, [d]Estimated as swine, [e]Estimated as equine, [f]Li et al. [44], [g]Assumed, [h]Deublein and Steinhauser [10], [i]Batzias et al. [45], [j]Estimated value.

**Table 5**
Agricultural crops and parameters for the calculation of potential of biogas generation.

| **Agricultural crops** ($l=\overline{1,n}$) | Reside-to-crop production ratio, $f$ ($kg$ $kg^{-1}$) | Sustainable rate removal $\Theta$ ($kg$ $kg^{-1}$) [a] | Volatile-to-total solid ratio S ($kg_{vs}$ $kg_{ts}^{-1}$) | Biomethane yield $M$ ($Nm^3_{CH_4}$ $kg_{vs}^{-1}$) |
|---|---|---|---|---|
| 1. Beer barley | 1.4 [a] | 0.40 [a] | 0.94 [d] | 0.229 [d] |
| 2. Barley | 1.4 [a] | 0.40 [l] | 0.90 [d] | 0.229 [d] |
| 3. Beans (for export) | 2.1 [b] | 0.40 [l] | 0.90 [l] | 0.174 [n] |
| 4. Beans (for internal consumption) | 2.1 [b] | 0.40 ** | 0.90 ** | 0.174 [n] |
| 5. Bread wheat | 1.3 [a] | 0.40 [l] | 0.92 [l] | 0.087 [f] |
| 6. Chickpeas | 2.1 [k] | 0.40 [l] | 0.90 [l] | 0.200 [e] |
| 7. Corn | 1.4 [a] | 0.50 [a] | 0.98 [d] | 0.317 [d] |
| 8. Grass pea | 2.1 [k] | 0.40 [l] | 0.90 [l] | 0.200 [l] |
| 9. Lentils | 2.1 [k] | 0.40 [l] | 0.90 [l] | 0.200 [l] |
| 10. Oats | 1.5 [a] | 0.40 [a] | 0.58 [f] | 0.203 [f] |
| 11. Others | 1.0 [l] | 0.40 [l] | 0.90 [l] | 0.200 [l] |
| 12. Others cereals | 1.0 [k] | 0.40 [l] | 0.70 [l] | 0.200 [l] |
| 13. Peas | 2.1 [k] | 0.40 [l] | 0.90 [l] | 0.200 [l] |
| 14. Potatoes | 0.4 [b] | 0.40 [l] | 0.90 [l] | 0.366 [g] |
| 15. Quinoa | 1.0 [k] | 0.40 [l] | 0.192 [i] | 0.241 [i] |
| 16. Rice (with peel) | 1.6 [a] | 0.50 [a] | 0.92 [d] | 0.195 [d,m] |
| 17. Rye | 1.8 [a] | 0.40 [a] | 0.92 [i] | 0.360 [h] |
| 18. Tapicoa | 1.0 [k] | 0.40 [l] | 0.90 [l] | 0.100 [l] |
| 19. Tricale | 1.3 [c] | 0.40 [l] | 0.93 [i] | 0.100 [l] |
| 20. White wheat | 1.3 [a] | 0.40 [a] | 0.92 [l] | 0.087 [f] |

[a]Scarlat et al. [11], [b]IPCC [46], [c]Wikström and Adolfsson [47], [d]Dinuccio et al. [48], [e]Deublein and Steinhauser [10], [f]Lehtomäki et al. [50], [g]Parawira et al. [51], [h]Petersson et al. [52], [i]Cropgen Database [53], [k]Assumed as beans, [l]Assumed, [m]Somayaji and Khanna [49], [n]López-Dávila et al. [54].

Information listed in Table 5 for the calculation was collected from literature [46–54].

*4.1.3. Technical potential of biogas from co-digestion of manure with crop residue*

As depicted in Fig. 3, the co-digestion involves mixing a co-substrate (crop residue in this case) into the manure with the purpose of improving the biogas yield. This enhancement can be explained because of the synergism in the reacting medium and the addition of some missing nutrients [55]. Nevertheless, the supplementary solid that can be added to the manure slurry is dictated by the operating conditions of the anaerobic technology being employed. In general terms, anaerobic digestion technologies are classified into wet-fermentation and dry-fermentation. While the former operates with a total solid concentration lower than 10%, the latter is adequate for a substrate with a total solid concentration greater than 20% [56]. The dominant technology for the treatment of agricultural residues is wet fermentation [57] and, for the national potential analysis, this was used as the reference for the assessment. Thus, a total solid concentration in the digester ($x^m$) of 15% as maximum limit was considered.

The information provided in Table 4 can be used to calculate the solid concentration of the manure for each type of livestock. For instance, the concentration of total solid for dairy manure is 14%, while swine is 13%. For the assumed humidity of agricultural residue, 15% (wet basis), its total solid concentration is 85%.

It can be demonstrated, by applying a mass balance (see Fig. 3), that the maximum amount of co-substrate tolerable for a wet-fermentation mixing manure and crop residue, and the total mixed substrate to digest can be calculated with the following equations:

$$m^{cs}_{max} = m^m \frac{(x^m - x_{max})}{(x_{max} - x^{cs})} \tag{5}$$

$$m^t = m^m \frac{(x^m - x^{cs})}{(x_{max} - x^{cs})} \tag{6}$$

In which $m^{cs}_{max}$ is the maximum amount of co-substrate to add for a wet-fermentation with manure; $m^m$ is the total available manure per farm; $x^m$is the total solid manure concentration; $x^{cs}$ is the total solid concentration of the co-substrate, in this case crop residue; and $x^{max}$ is the maximum total solid concentration within the reactor for a wet co-fermentation (set up at 15% as previously indicated).

The availability of both the substrate and the co-substrate for co-digestion, i.e. manure and crop residue, depends essentially on the geographical distribution of farms and annual crops. The co-substrate cannot necessarily be supplied at the required rate because of the large transportation distance (in practical terms), or simply because the co-substrate is not available where the farm is located. Due to the fact that the assessment was conducted using the county as the smallest geo-administrative control area, a necessary condition for the co-digestion was that the total biomass (crop residue in this case) in each county ($m_i$) must be at least equal to the maximal amount of co-substrate to be added ($m^{cs}_{max}$) to the total of the farm-based units within that county. The latter can be

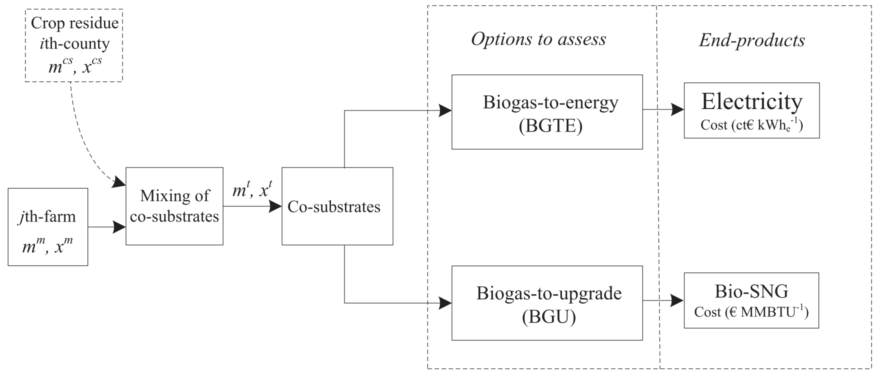


**Fig. 3.** Conversion pathway for co-digestion of manure and agricultural residue.

expressed by a Boolean operator ($A_c$) to differentiate when the co-digestion can be performed or not, as indicated by Eq. 7 and Eq. 8.

$$\pi_{t,j}^{BTE} = \sum_j m_j^t S_c R_c \Delta \tilde{H}_{LHV}^{CH_4} \eta_a \, \eta_e \, A_e A_c \quad \begin{cases} A_e = 1; \forall \pi_{t,j}^{BTE} \geq 8 \text{ kW}_e \\ A_e = 0; \forall \pi_{t,j}^{BTE} < 8 \text{ kW}_e \\ A_c = 1; \forall m_i \geq \sum\limits_{i,j} m_{max\ ,j}^{cs} \\ A_c = 0; \forall m_i < \sum\limits_{i,j} m_{max\ ,j}^{cs} \end{cases} \tag{7}$$

$$\pi_{t,j}^{BGU} = \sum_i m_j^t S_c R_c \eta_a A_u A_c \quad \begin{cases} A_u = 1; \forall\ \pi_{t,j}^{BGU} > 5 \text{ Nm}^3_{CH_4} \text{ h}^{-1} \\ A_u = 0;\ \forall\ \pi_{t,j}^{BGU} \leq 5 \text{ Nm}^3_{CH_4} \text{ h}^{-1} \\ A_c = 1;\ \forall\ m_i \geq \sum\limits_{i,j} m_{max\ ,j}^{cs} \\ A_c = 0;\ \forall\ m_i < \sum\limits_{i,j} m_{max\ ,j}^{cs} \end{cases} \tag{8}$$

In which $R_c$ corresponds to the yield of biomethane for co-digestion estimated in 205 $\text{Nm}^3_{CH_4}$ $\text{kg}_{vs}^{-1}$ as a representative value [50], and $S_c$ is the volatile-to-total solid ratio calculated for the mixing of manure and crop residue.

The technical energy potential of the entire country derived from the mono-digestion of crop residue either from the *biogas-to-energy* or *biogas-to-upgrade* route can be calculated by totalling the technical potential for all the *i*th-counties, as Eq. (9) indicates. Similarly, by totalling the technical potential of all *j*th-farms, the technical potential for the mono or co-digestion of manure can be calculated as in Eq. 10.

$$\text{Mono}-\text{digestion of crop residues} \\ \Pi_t^{BTE} = \sum_i \pi_{t,i}^{BTE} \qquad \Pi_t^{BTU} = \sum_i \pi_{t,i}^{BTU} \tag{9}$$

$$\text{Mono}-\text{digestion of manure.} \\ \text{Co}-\text{digestion of manure with} \\ \text{crop residue} \\ \Pi_t^{BTE} = \sum_j \pi_{t,j}^{BTE} \qquad \Pi_t^{BTU} = \sum_j \pi_{t,j}^{BTU} \tag{10}$$

### 4.2. Methodology for the economic analysis

The unitary cost of production of secondary energy was estimated by applying the economic model shown in Eq. (11).

$$c\pi_t = \alpha I + C_{o\&m} + C_p - R \tag{11}$$

In this model, $c$ corresponds to the unitary cost of production; $\pi_t$ corresponds to the technical potential; $\alpha$ is the capital recovery factor; $C_{o\&m}$ is the operation and maintenance cost; $C_p$ is the procurement cost of biomass at the processing point; and $R$ represents the revenues potentially obtainable from selling by-products such as heat or digestate.

To estimate investment, operation and maintenance cost as well as conversion efficiencies for all the unit operations that compose the two pathways under assessment (i.e. *biogas-to-energy* and *biogas-to-upgrade*), economic and technical data were drawn on from literature and technical reports, and mathematically correlated as summarised in Table 6. An interest rate of 10% ($i$) with 8,000 h of operation and a 15-years lifespan ($n$) were used to evaluate the two pathways. Because the investment was estimated from plants installed in Europe, a location factor of 1.08 was included to address extra cost resulting from freight, taxes and insurance [58]. The yearly operation and maintenance cost was estimated as a fraction of the total investment, a method normally employed in assessment at pre-feasibility level [59,60]. For the *biogas-to-energy* pathway, a reciprocating Otto-engine was assumed for electricity generation since it is a proven technology. Similarly, for the *biogas-to-upgrade* route, information on applicable technologies was correlated. Whilst the dissimilar chemical principle of the operation of carbon dioxide separation process, it was assumed that there were no significant differences in the cost of processing; a fact backed up by empirical evidence [61,62].

The mono and co-digestion of crop residue implies the intermediate steps (depending on the harvesting system) of collecting, hauling, packing, on-farm transportation and on-road conveyance of biomass to a processing facility (as it is irregularly distributed across large areas) incurring an additional cost for the biogas production. Under these circumstances, it is necessary to estimate the cost of crop residue procurement by proposing a simplified model for the operations associated to its collection from the field after the annual harvesting to its supply to the gate of plant. To do this, it was assumed that the shape of each county can be approximated through a square of side $l$, and with a surface equivalent to that of the county. Moreover, it was assumed that all the available biomass after harvesting had a homogeneous superficial density (measured for instance as t m$^{-2}$), and it was conveyed to the geometric centre of the county, and thus the geometric centre of the square. Assuming a tortuosity of 0.85 for on-road transportation, it is possible to demonstrate, after applying some integral calculus, that the average displacement distance for the transportation of biomass $\overline{d_s}$ at county-level can be calculated by Eq. (12) [63].

$$\overline{d_{s,i}} = \frac{1}{6} l_i \tau (\sqrt{2} + \ln(1 + \sqrt{2})) \tag{12}$$

Similarly, using a circle to approximate the share of a county, it is possible to demonstrate that the average distance is roughly 20% less when compared to the square-approximation (evaluated as the average area of the county). Hence, the square-approximation was chosen because it is a more conservative estimate.

**Table 6**
Parameters employed for the techno-economic assessment. Correlation index ($r^2$), number of data and limits of validity below each correlation were added. Investment ($I$) was expressed as a function of the output methane flow of each unit ($Nm^3_{CH_4}$). For the reciprocating unit, technical and economic data was correlated as function of output power($kW_e$).

| Option to assess | Item | Correlation | Source |
|---|---|---|---|
| *Biogas-to-energy* | *Energy generator investment Reciprocating unit (I)* | $I(€\ kW_e^{-1}) = 15,648x^{-0.536}[x, kW_e]$<br>$r^2$=n.a.; n= 127; [8 $kW_e$; 2 $MW_e$] | a |
| | *Operation and maintenance cost ($C_{o\&m}$)* | $C_{o\&m}(ct€\ kWh_e^{-1}) = 17.053x^{-0.478}[x, kW_e]$<br>$r^2$=n.a.; n= 127; [8 $kW_e$; 2 $MW_e$] | a |
| | *Average electrical efficiency ($\eta_e$)* | $\ln(\eta_e) = -0.6563 - 1.5670 \ln(x)^{-1}[x, kW_e]$<br>$r^2$=0.7953; n=215; [8 $kW_e$,8.92 $MW_e$] | a |
| *Biogas-to-upgrade* | *Digester (I)* | $I(€) = 18,248x^{0.8586}[x, Nm^3_{CH_4} h^{-1}]$<br>$r^2$=0.9832; n=14; [53 $Nm^3_{CH_4}$ $h^{-1}$, 1,060 $Nm^3_{CH_4}$ $h^{-1}$] | b,c |
| | *Annual operation and maintenance cost ($C_{o\&m}$) digester* | 13% Investment (I) | b,c |
| | *Upgrading unit (I)* | $I(€) = 83,268x^{0.4793}[x, Nm^3_{CH_4} h^{-1}]$<br>$r^2$=0.855; n=9; [152 $Nm^3_{CH_4}$ $h^{-1}$, 1,220 $Nm^3_{CH_4}$ $h^{-1}$] | b,c |
| | *Annual operation and maintenance cost ($C_{o\&m}$) upgrading* | 25% investment (I) | b,c |
| | *Injection into the net (I)*<br>*45 bar max. network pressure and 1 km length* | $I(€) = 970.5x^{0.997}[x, Nm^3_{CH_4} h^{-1}]$<br>$r^2$=0.997; n=3; [305 $Nm^3_{CH_4}$ $h^{-1}$; 1,992 $Nm^3_{CH_4}$ $h^{-1}$] | b,c |
| | *Annual operation and maintenance cost ($C_{o\&m}$) injection* | 3% investment (I) | Assumed |

[a]ASUE [41], [b]Urban et al. [61], [c]Althaus and Urban [62].

For the specific on-road transportation cost ($c_e^t$), 1.8 € km$^{-1}$ was considered as representative according to Hetz et al. [64]. This value, when multiplied by the average displacement distance (Eq. (12)), leads to the total on-road transportation cost of biomass.

The majority of information available on the cost of collecting biomass is focused on wheat straw and corn stover because they are the dominant crops in a substantial number of counties [11,65]. Although crop residue has diverse characteristics affecting the cost of recovery, transportation and processing, the cost of its collection from the field (which includes preparing, packing and on-farm transportation) of all crop residue was approximated without distinguishing their differences to wheat straw because of the lack of more specific data. Hetz et al. [64] reported that the cost of collecting wheat straw after harvesting was in the 6–10 € t$^{-1}$ range, hence a value of 8 € t$^{-1}$ was approximated for the assessment.

Therefore, the total procurement cost of crop residue, which includes collecting and on-road conveyance, can be estimated using Eq. (13).

$$C_{p,i} = c_e^t \overline{d}_{s,i} m_i + c_e^r m_i \tag{13}$$

In which $C_{p,i}$ is the procurement cost of biomass at the gate of plant in the $i$th-county; $c_e^t$ is the specific on-road transportation cost; $\overline{d}_{s,i}$ is the average displacement distance for the transportation of biomass within the $i$th square-approximated county; $c_e^c$ is the specific biomass collecting cost; and $m_i$ is the total crop residue available yearly within the $i$th-county.

Afterwards, the gathered information and biomass supply model was integrated into the economic modelling previously presented (see Eq. (11)) for the calculation of the distribution of the unitary cost of production for all the sources of biomass under investigation. Revenues from heat and digestate by-products were not considered in the cost estimation. Firstly, because there is no established market for the commercialisation of surplus heat in the country (i.e. district heating), and secondly, due to the fact that the sale of digestate plays only a marginal role in terms of the economics of the process [17] and its use is not regulated in Chile yet.

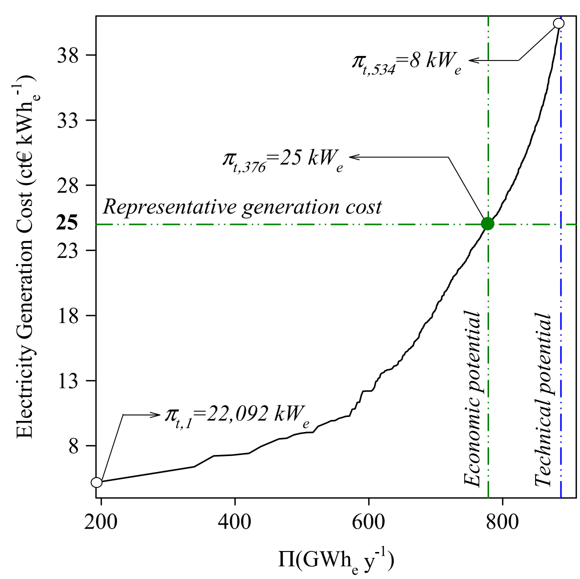


**Fig. 4.** Supply–cost curve for the *biogas-to-energy* pathway by mono-digestion of manure.

### 4.3. Calculation of representative generation cost and GIS data

Considering the empirical facts laid out by Izquierdo et al. [66] for renewables, the statistical mode of a log-normal distribution of cost will be considered as the *representative generation cost* of the conversion pathways to be assessed. It can be calculated through the following expression:

$$c_r = \text{mode}[c_i(\pi_{t,i})] = e^{\mu - \sigma^2} \quad i = \overline{1, n} \tag{14}$$

In which $c_r$ is the representative generation cost; $c_i(\pi_{t,i})$ is the unitary cost of production for the $i$th-technical potential; and $\mu$ and $\sigma^2$are the average and variance of the production cost of the totality of single potentials ($n$) within the frame of evaluation. The economic limit can be worked out directly by interpolating the

representative generation cost with the supply–cost curve. More detailed information about the mathematical procedure for the construction of the supply–cost curves and limit of potential can be found elsewhere [63,66].

Finally, the information was incorporated into a geographical information system (GIS) to locate and highlight areas with lower or higher energy potential. These energy maps were built by using the county as the smallest geo-administrative control area of the country, 364 in total with an average surface area of 2,100 $km^2$ [67]. The name of the region, which comprises several counties, was indicated by Roman numerals on the map (see Table 1).

## 5. Results

Figs. 4 and 5 display the supply–cost curves for the *biogas-to-energy* and *biogas-to-upgrade* pathways assessed for the mono-digestion of manure. The technical potential for the former option reached 887 $GWh_e\ y^{-1}$, whereas its economic potential bordered 780 $GWh_e\ y^{-1}$ at a representative generation cost of 25 ct€ $kWh_e^{-1}$. For the *biogas-to-upgrade* route the technical limit reached 225 MM $Nm^3\ y^{-1}$ with economic potential reaching 182 MM $Nm^3\ y^{-1}$ at a representative generation cost of 98 € $MMBTU^{-1}$.

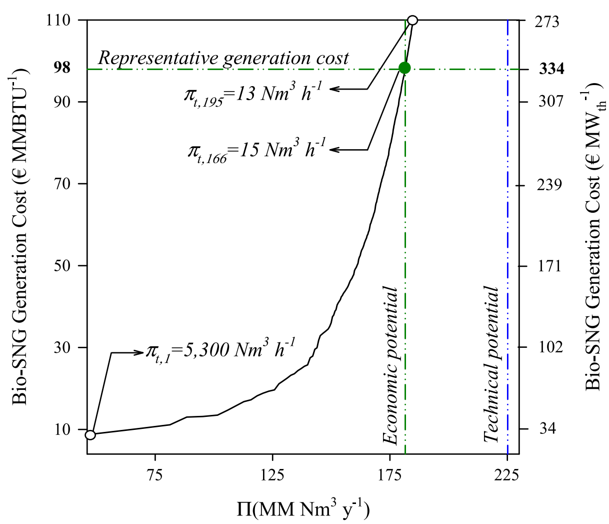


**Fig. 5.** Supply–cost curve for *biogas-to-upgrade* pathway by mono-digestion of manure.

Fig. 6 and 7 reveal that the technical potential from manure processing is highly concentrated in Región Metroplitana (XIII), accounting for approximately 62% and 64% of the total electricity and Bio-SNG production respectively. In second place is Región de la Araucanía (IX), which possesses 11% and 10% of the electricity and Bio-SNG technical potential.

Additionally, it was found that at national level the technical potential of electrical power was heavily concentrated on the small-scale, in the 10 – 250 $kW_e$ range, and accounted for 71% of the country's total. A similar concentration was observed in the technical potential of Bio-SNG, where approximately 80% of the potential was on a scale lower than 1 MM $Nm^3\ y^{-1}$, with only 12% in the 1–2.7 MM $Nm^3\ y^{-1}$ range.

For the mono-digestion of agricultural residue, the technical potential of electricity reached 1,360 $GWh_e\ y^{-1}$ and the economic potential 1,112 $GWh_e\ y^{-1}$ at a representative generation cost of 15. 4ct€ $kWh_e^{-1}$ (see Fig. 8). Meanwhile, the generation of Bio-SNG from this substrate offered a technical potential of 351 MM $Nm^3\ y^{-1}$ and an economic potential of 280 MM $Nm^3\ y^{-1}$ at a representative generation cost of 40 € $MMBTU^{-1}$ (see Fig. 9). A high concentration of this technical potential was observed in the low-power range (10–250 $kW_e$) and accounted for 46% of the total. However, the 500 $kW_e$ to 5 $MW_e$ range accounted for 33% of the total technical potential. For the Bio-SNG option, more than 57% of the potential was concentrated in a range lower than 1MM $Nm^3\ y^{-1}$, followed by 22% at the 1.0–2.7 MM $Nm^3\ y^{-1}$ scale. Geographically, the technical potential of electricity and Bio-SNG was concentrated in the Región de O´Higgins (VI ) (32%), Región del Maule (VII) (19%) and Región de la Araucanía (IX) (18%), with these three regions representing almost 70% of the total, as seen in Fig. 10 and Fig. 11.

The possibility of co-digesting manure with agricultural residue offered an increase in the economic limit for the electricity

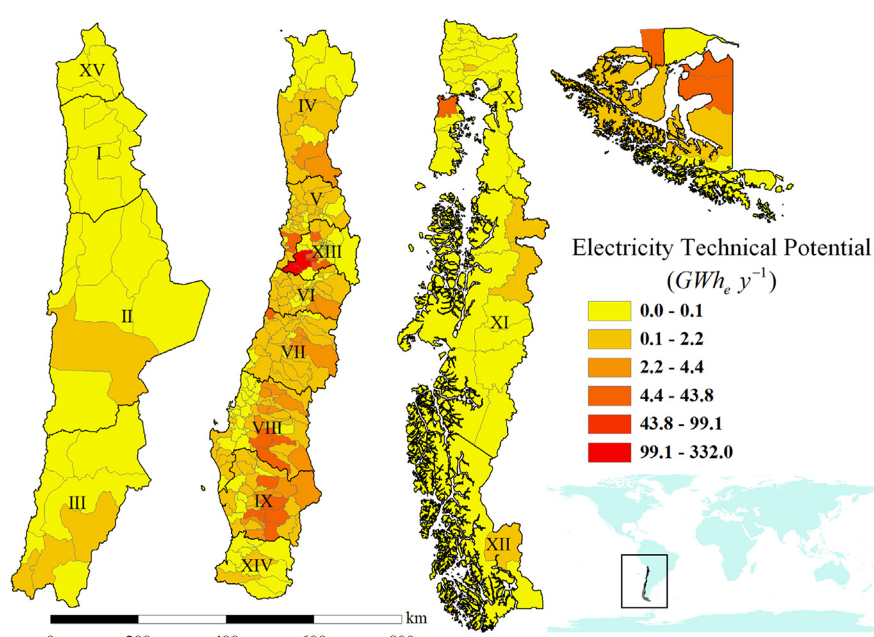


**Fig. 6.** Technical potential of electricity from mono-digestion of manure.

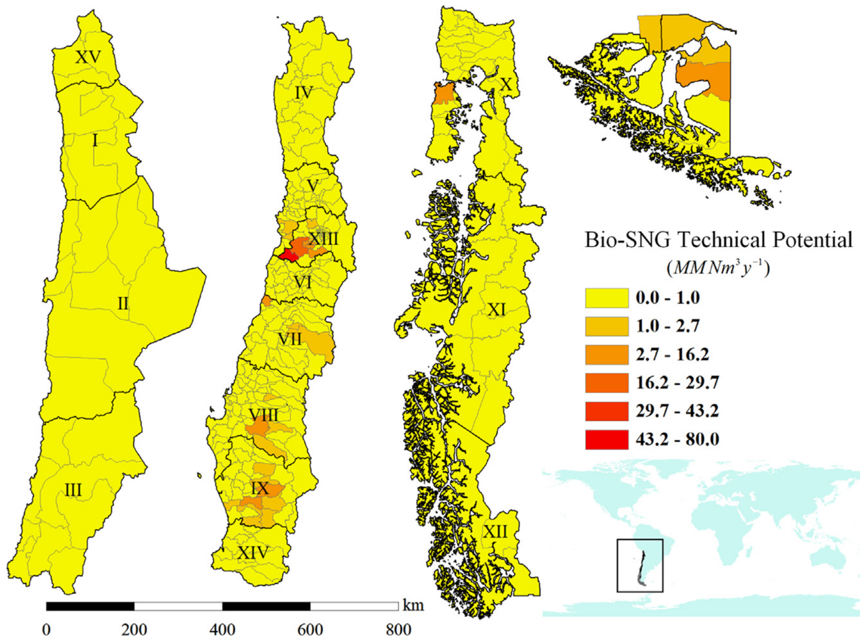


**Fig. 7.** Technical potential of Bio-SNG option from mono-digestion of manure.

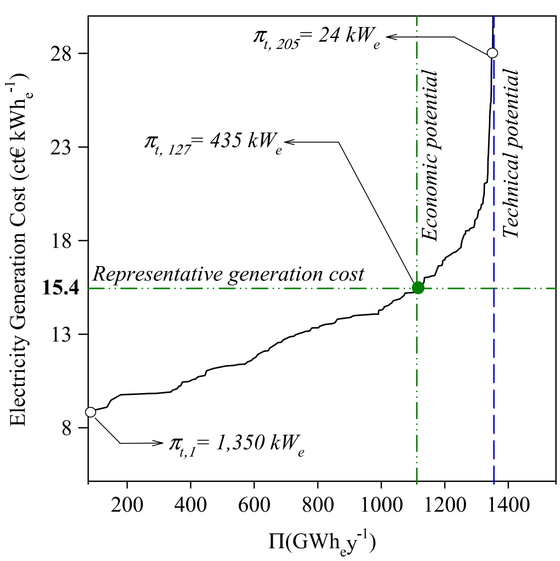


**Fig. 8.** Supply–cost curve for *biogas-to-energy* pathway by mono-digestion of agriculture residue.

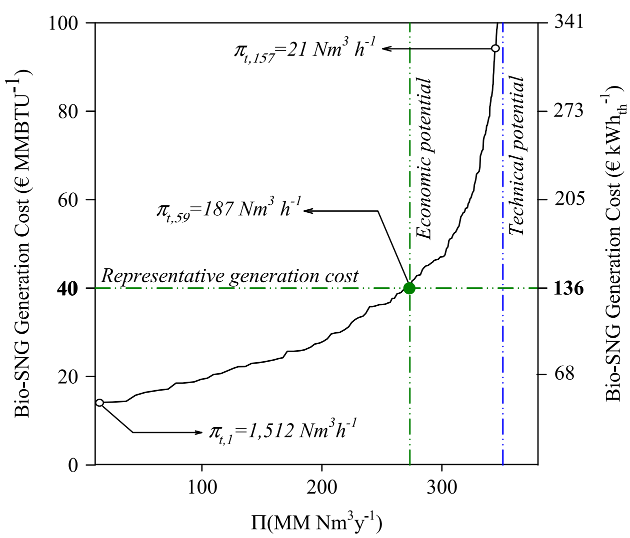


**Fig. 9.** Supply–cost curve for the *biogas-to-upgrade* pathway by mono-digestion of agricultural residue.

generation option whilst providing the same representative generation cost as the mono-digestion of manure. As can be observed in Fig. 12, the co-digestion raised this economic potential from 780 GWh$_e$ y$^{-1}$ to 1,338 GWh$_e$ y$^{-1}$ at a representative generation cost of 25 ct€ kWh$_e^{-1}$. This greatly increased the number of biogas plants that could achieve the minimal technical conditions necessary to operate. As seen in Fig. 4, the economic limit of *biogas-to-energy* from mono-digestion of manure was made up of 376 plants (farms), with nominal capacities from 22 MW$_e$ to 25 kW$_e$. On the other hand, and as illustrated in Fig. 12, the economic limit of *biogas-to-energy* via co-digestion accounts for 1,108 plants with nominal capacity in a similar power range.

Although the increase in electrical potential from co-digestion was significant at 46%, the power capacity was still concentrated in the low range capacity and accounted for 39% in the 10–250 kW$_e$ range, and 31% in power lower than 10 kW$_e$. Potentials exceeding 5 MW$_e$ were exceptional, and constituted less than 3% of the total technical potential.

The assessment of the *biogas-to-upgrade* route was conducted following the same methodological approach applied to the *biogas-to-energy* pathway by considering co-digestion. However, the results led to an increase in the Bio-SNG potential, principally in the low range, with the consequence that the representative generation cost reached extremely high and empirically unprecedented levels. Nevertheless, counties were found where it would still be possible to develop Bio-SNG exploitation projects on a commercial scale although they represented no more than 15% of the total technical potential. As with the mono-digestion option, just two regions accounted for more than 61% of the technical potential. Those were RM Región Metropolitana (XIII) and Región de la Araucanía (IX) (see Figs. 13 and 14).

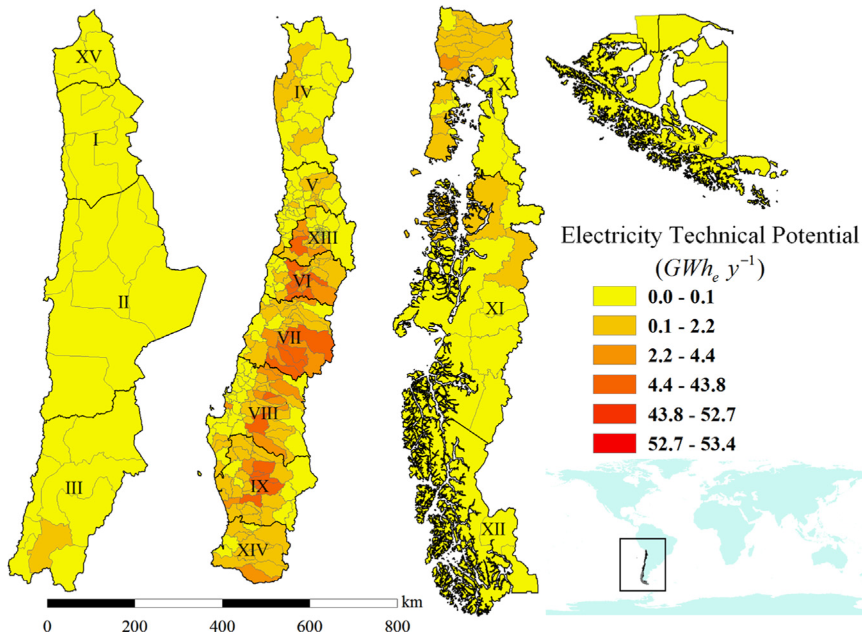


**Fig. 10.** Technical potential of electricity from mono-digestion of agricultural residue.

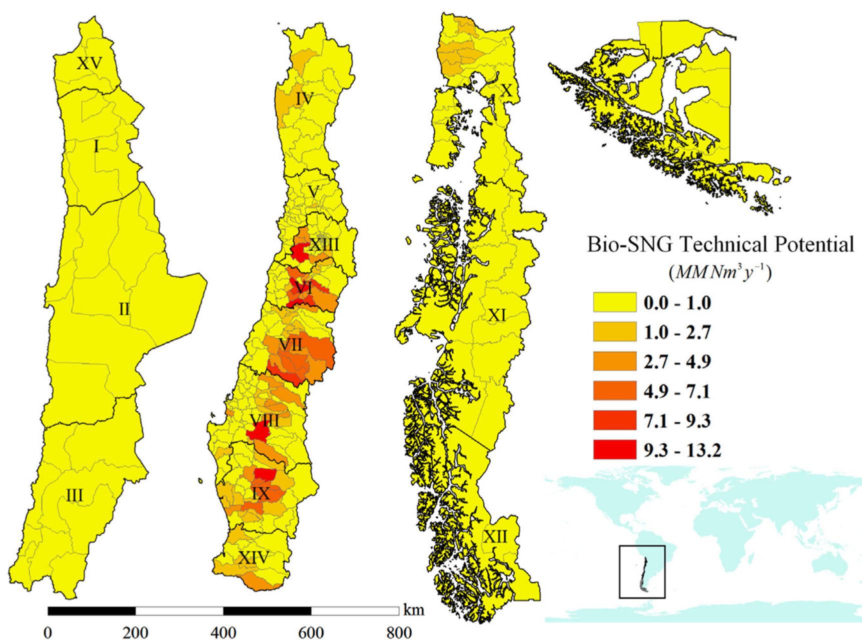


**Fig. 11.** Technical potential of Bio-SNG from mono-digestion of agricultural residue.

Table 7 summarises the main economic indicators obtained from the assessment for the mono-digestion of the two substrates (i.e. manure and crop residue) and their co-digestion.

## 6. Discussions

Having applied a analysis potential methodology for a cross-economic comparison of two energy options for obtaining energy from agro-industrial residue (i.e. electricity and an upgraded biogas), the main macro-economic indicators and its features were outlined in this research.

Only a small number of the total farms in the country (fewer than 1%) were found to have adequate conditions for developing biogas projects. This is because the majority of them were constituted of only a limited quantity of livestock, which severely restricted the amount of technically feasible biogas units. Additionally, a large proportion of the technical potential of electricity for both mono-digestion and co-digestion could be found in the low scale, the $10-250\ kW_e$ range, and strongly concentrated in only some geographical areas. A similar tendency was also observed for the possibility of producing Bio-SNG, for which the scale rarely surpassed 1 MM $Nm^3\ y^{-1}$ and was concentrated in a small number of regions.

Exceeding the cost of production in most cases the market price of natural gas (Fig. 5 and Fig. 9), currently ranging from 12 to 22 € $MMBTU^{-1}$ roughly, the Bio-SNG option seems hardly competitive without subsidies. More importantly, approximately 80% of this technical potential (Bio-SNG) is in a range lower than 1 MM $Nm^3\ y^{-1}$, a scale that is not commercially attractive for such

projects, at least in practical terms. For the electricity alternative, it was observed that a significant fraction of the economic potential that could be profitable when considering a referential market price of electricity of 12 ct€ $kWh_e^{-1}$, representative for projects at the low scale. Consequently, this is the most attractive aspect of the potential and it should therefore be targeted for enhancing biogas production.

Regarding co-digestion, this process can significantly increase the number of biogas units since the conditions to simultaneously supply the required substrates are present. Moreover, the co-digestion of agro-industrial residue can be taken advantage of because it may bring higher potential methane yield through technical improvements and can offer major operational stability.

The analysis of potential was conducted for the decentralised generation of biogas using manure, and for co-digestion with crop residue. Another option worthy of assessment is the centralised use of manure as substrate, which may improve the economics of the whole process. However, this option implies a location analysis for a centralised-processing plant, something normally associated with optimisation problems under geo-spatial restrictions. Furthermore, centralised manure usage involves the additional cost of transportation of a slurry with low solid content, and potential instability in the substrate supply because it involves dependency on third-parties, contracts and the creation of business models and mechanisms of partnership affiliation.

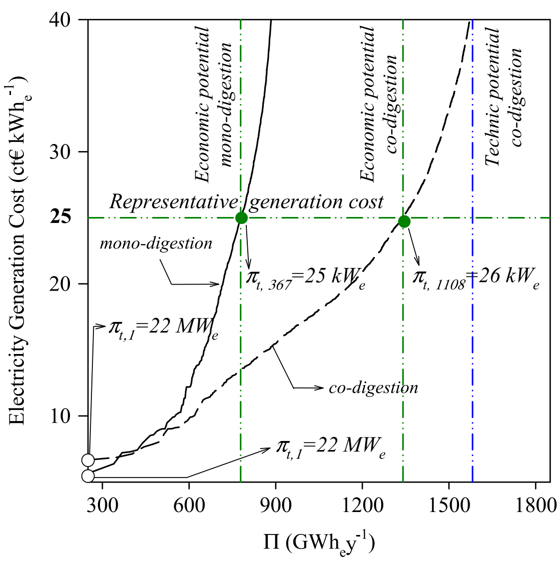


**Fig. 12.** Supply–cost curve for the electricity generation of co-digestion of manure and agricultural residue.

The great variability of biomethane yield from manure digestion and crop residues is well-known and is linked principally with the sort of substrate and operating conditions of the reactor. Thus, the presented results should be considered referentially, taking into consideration the limitations intrinsically related to the technologies used for the evaluation and their economic implications. Additionally, the economic figures were calculated assuming stability in the supply of biomass and plant capacity, which were interpolated from discrete data. In reality, biogas plants are normally offered by technological suppliers at a fixed nominal capacity and have to come up against instability in the supply of substrates, variability of composition of the feedstock, reduction of reactor performance and unexpected shutdowns, all which negatively influence production cost.

## 7. Conclusions

The dichotomy of biogas for electricity and biogas for upgrading for the framework under analysis was tackled. The study revealed a pattern of results which could be interpreted in the following way:

Firstly, the option of producing electricity seems more economically advantageous than that of producing Bio-SNG. This is so for a large fraction of the technical potential in which agro-industrial biomass is available in the country. Furthermore, this tendency is irrespective of the implementation of a subsidisation mechanism such as a feed-in tariff or such like. Apart from this, the possible products of interest from farms (electricity and heat) and methods of using them (for self-generation or sale for the injection into the electrical network) bring major flexibility to energy projects when compared to the option of solely producing an upgraded gas.

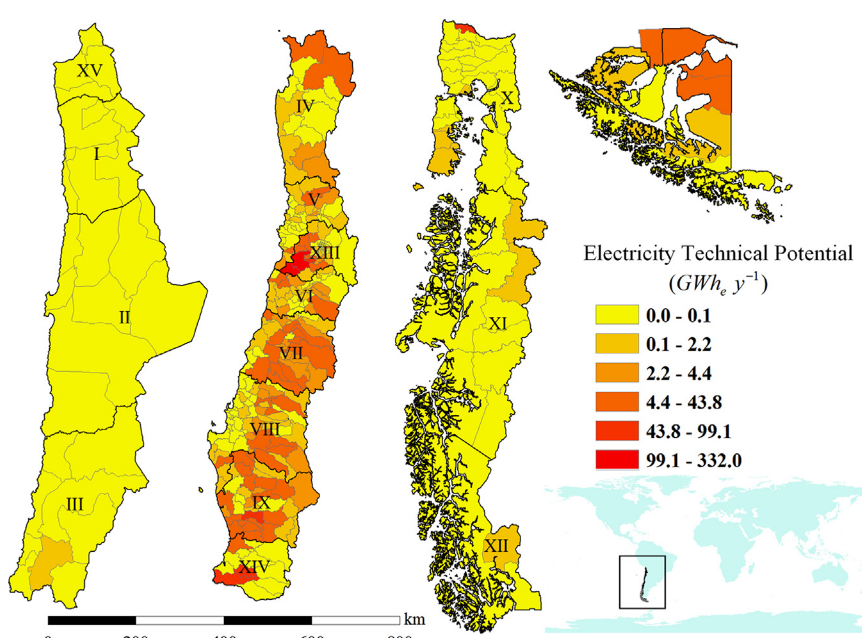


**Fig. 13.** Technical potential of electricity from co-digestion of manure and agricultural residue.

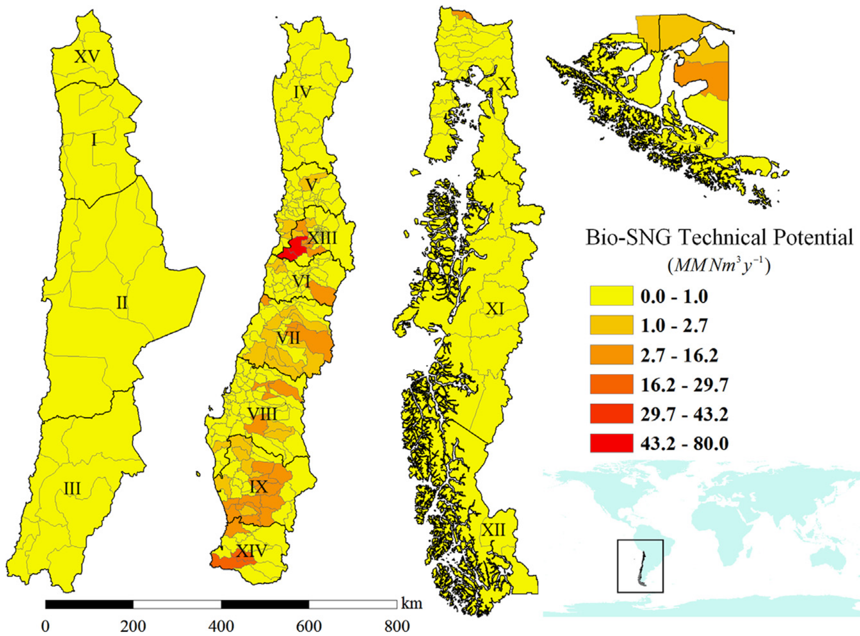


**Fig. 14.** Technical potential of Bio-SNG from co-digestion of manure and agricultural residue.

**Table 7**
Energy potential of the three assessed biomass sources for energy generation.

| | Economic indicator | Electricity generation *Biogas-to-energy* | Fuel generation *Biogas-to-upgrade* |
|---|---|---|---|
| *Mono-digestion of manure* | Technical potential | 0.9 $TWh_e\ y^{-1}$ | 225 MM $Nm^3\ y^{-1}$ |
| | Economic potential | 0.8 $TWh_e\ y^{-1}$ | 182 MM $Nm^3\ y^{-1}$ |
| | Representative cost | 25.0 ct€ $kWh_e^{-1}$ | 98 € $MMBTU^{-1}$ |
| *Mono-digestion of agricultural residue* | Technical potential | 1.4 $TWh_e\ y^{-1}$ | 351 MM $Nm^3\ y^{-1}$ |
| | Economic potential | 1.1 $TWh_e\ y^{-1}$ | 280 MM $Nm^3\ y^{-1}$ |
| | Representative cost | 15.4 ct€ $kWh_e^{-1}$ | 40 € $MMBTU^{-1}$ |
| *Co-digestion of manure and agricultural residue* | Technical potential | 1.6 $TWh_e\ y^{-1}$ | 440 MM $Nm^3\ y^{-1}$ |
| | Economic potential | 1.3 $TWh_e\ y^{-1}$ | MM $Nm^3\ y^{-1}$ |
| | Representative cost | 25 ct€ $kWh_e^{-1}$ | n.a. |

Secondly, the high concentration of biomass in only a few zones suggests that the implementation of a bioenergy policy ought to be focused on zones of developmental priority, organised hierarchically according to their potential or using other such criteria in order that the bioenergy programmes for agro industries should be articulated with a high level of autonomy by local governments although coordinated by a central entity in such a way that they can become consistent with a national bioenergy policy that involves the use of biomass of different origins (municipal solid waste, industrial waste, wastewater treatment plant sludge, etc.).

Thirdly, there are a significant number of biogas projects which exhibit a production cost that would make them competitive under current market conditions, thus without the necessity of subsidies. This group of projects should be targeted as a matter of priority in order to enhance the introduction of biogas into the energy system of the country and, consequently, the share of renewables.

Therefore, given the aforementioned results and conclusions, and taking into consideration the limited availability of agricultural land in Chile, it is recommended that the skeleton of a macro-policy for the generation and enhancement of biogas use in the farming and agricultural sectors in the near future should be based on a *biogas-to-energy* approach, so for the production of electricity.

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